MIPP-NOTE-ANA-141

Chamber Tuning and Alignment

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Abstract

This document describes procedures and algorithms that were done to calibrate chamber time offsets, wire plane alignment, alignment of z positions and xy-rotation of the 9 MIPP wire chambers.

1 Drift Chamber Time Offsets

Time offsets in drift chambers serve two purposes:

- Improve signal to noise by grouping wires with similar times into a track;
- Improve track position and momentum resolution by using drift time in the track fit.

Figure 1 shows distribution of wire hit times for planes 1 of the 7 drift chambers (BC1-3 and DC1-4) for all runs. It is evident that each wire requires a different time offset. While wires in BC's can be grouped in eights, in DC's no such grouping seems to work. Furthermore, Figure 2 shows that there is significant variation in time offsets from run to run, hence in general time offsets vary with run and wire and require an automated procedure for the 9728 wires.

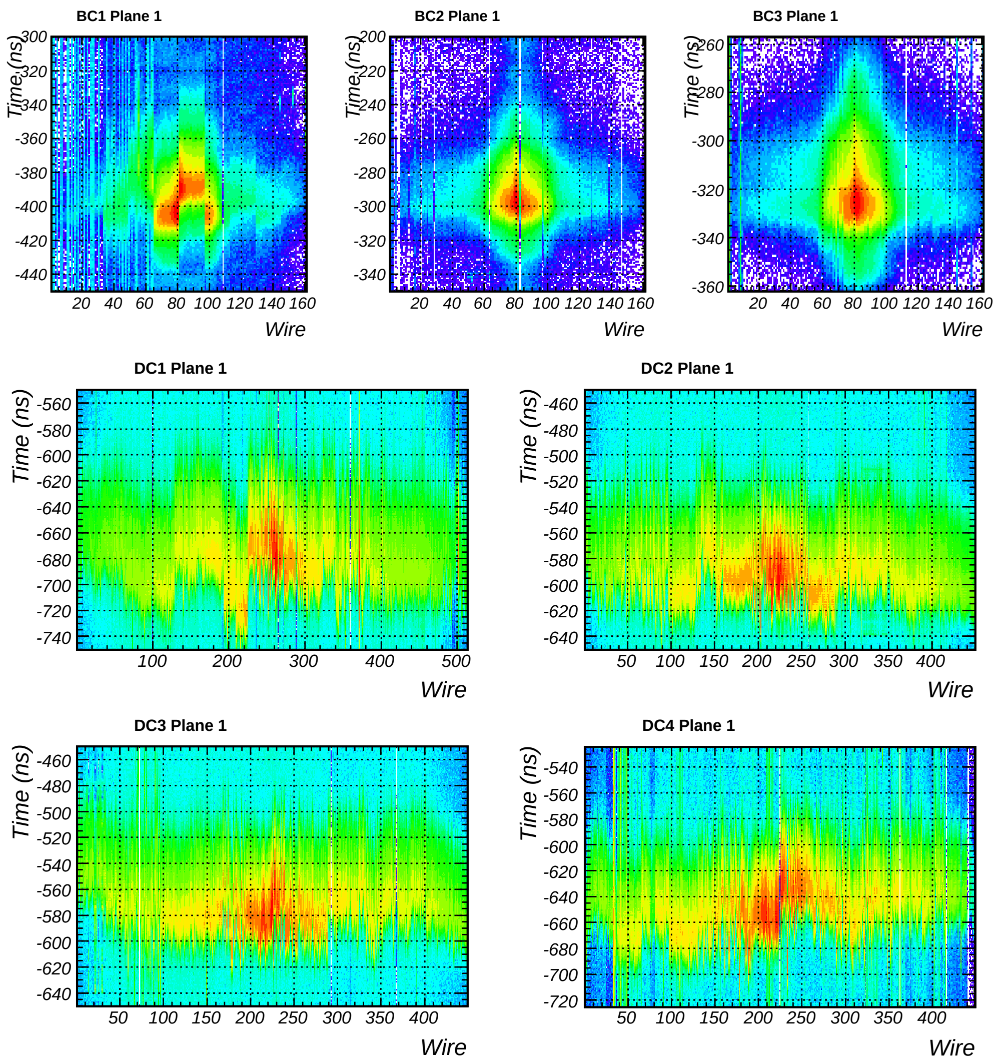

Figure 1: Raw chamber plane time distributions combined for all runs.

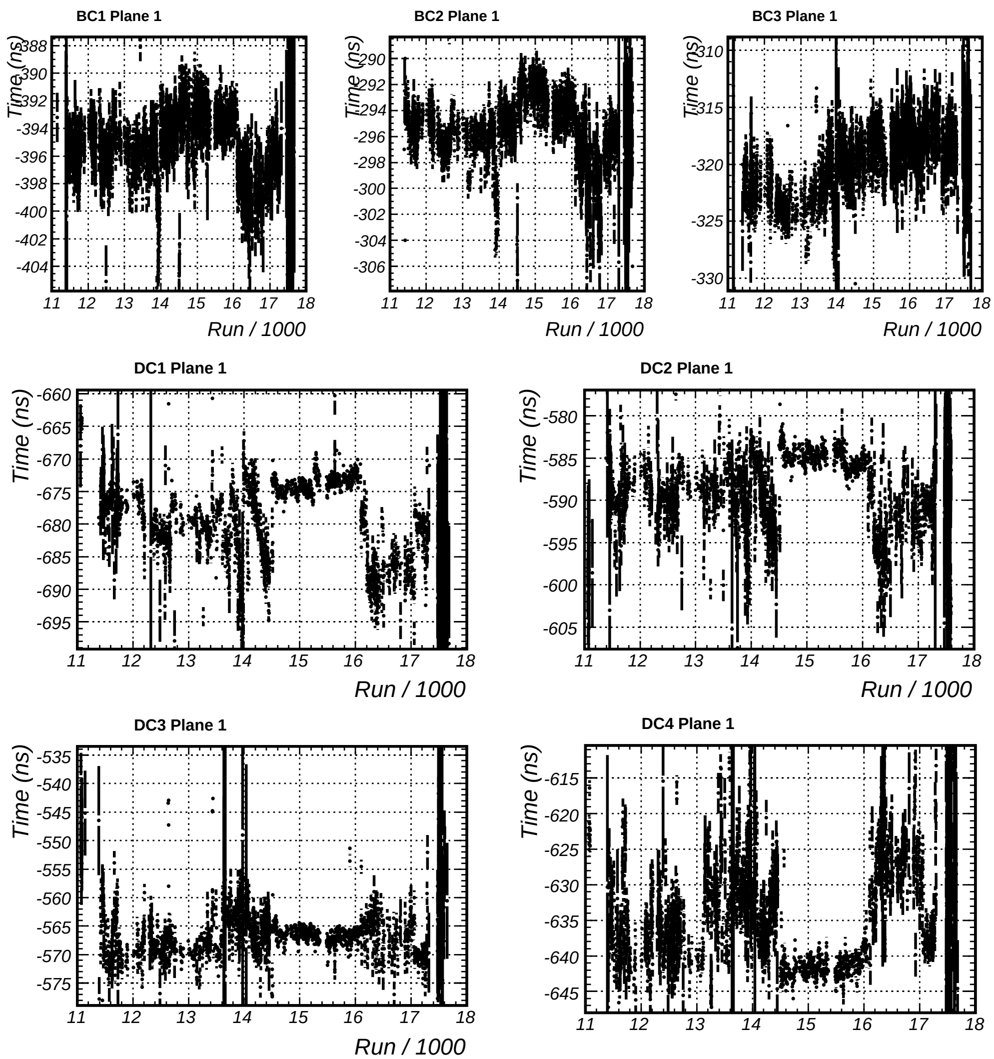

Figure 2: Raw chamber plane time averaged over a run.

1.1 Software in Pass 1

`DCTimeCalib` module in `ChamCalib` package was used to select events and write out a histogram for each wire in every run. `DCTimeCalib` depends only on `TrigReco/TrigDoT0` module, which computes event trigger time. Trigger time can differ by a few nanoseconds, so it is appropriate to subtract wire TDC value from trigger time[1].

`DCTimeCalib` created an array for every wire of every plane to count the number of times a given wire had a given time. This is faster than creating thousands of histograms right away because ROOT has to change folders when switching context from one JobCModule to another and this was significantly slowing down `anamipp`. In `EndRun()` function, arrays were converted to histograms, and histograms were grouped into chamber/plane folder hierarchy for easier navigation.

1.1.1 Event Selection

Event selection did not rely upon any reconstruction (which one might be able to use to improve t_0's in the future), but the following criteria were imposed to try to improve signal to noise ratio.

- No more than two $T01_{3/4}$ or $TBD_{3/4}$ are allowed in the event;
- If there were two 3/4 signals in either counter, time separation between the two had to be at least 100 ns;
- If a beam chamber had more that 24 wires hit, it is ignored;
- If a drift chamber had more 150 wire hit, it is ignored.

Although a significant fraction of data was thus ignored, the signal to noise ratio was much higher than if all the available data were used. Given the fact that wires on the edge of the chamber have little signal to begin with, it was extremely important to try reject noise so that the signal doesn't get buried underneath.

[1]Chamber electronics was running in common stop mode.

1.2 Extracting Time Offsets

With no single run has enough statistics to determine t_0 for every wire, some sort of joint analysis is required to extract time offsets. The approach I took was to take all the runs processed in Pass 1 and combine all histograms for each chamber plane into one tree (test binary `dcHistoToTree` in `ChamCalib`). Having one 1.3 GB file is somehow easier than 2900 files.

The last step in the process is running `dcTimeAna` from `ChamCalib`. The algorithm makes an assumption that from run to run relative wire times in a chamber plane do not change significantly. Then for wires which do not have enough statistics in any given run, the task is reduced to finding a run time offset and relative wire offset and set $t_0 = t_{0,run} + t_{0,wire}$. Here is the outline of my algorithm

1. In each run we attempt to determine t_0 for wires which have enough statistics;
2. For each run where at least 3 wires were fit, we compute the average $t_{0,run}$ for the run;
3. For every wire in the runs which have the run offset computed, we compute overall offset for the wire ($t_{0,wire}$ by shifting entries from different runs by $t_{0,run}$.
4. For every run, we use wires with valid $t_{0,wire}$ to recalculate $t_{0,run}$;
5. Steps 3 and 4 are repeated three times, each subsequent iteration picks up more runs and wires;
6. For every wire in every run, time offset is set to t_0 if it was computed in step 1, otherwise it is set to $t_{0,run} + t_{0,wire}$, thus taking into account differences from run to run and from wire to wire.

1.2.1 Fitting

Wire time distributions can be modeled quite well by a Gaussian with exponential tail, i.e.

$$f(t) = \begin{cases} A \cdot \exp\left(-\frac{1}{2}\left(\frac{t-t_{peak}}{\sigma_t}\right)^2\right), & t < t_{peak} + \sigma_{cut}\sigma_t \\ A \cdot \exp\left(\frac{1}{2}\sigma_{cut}^2 - \frac{t-t_{peak}}{\sigma_t}\sigma_{cut}\right), & t \geq t_{peak} + \sigma_{cut}\sigma_t \end{cases} \tag{1}$$

Here t_{peak} is the usual Gaussian peak, and σ_{cut} is a unitless parameter which determines how many sigma to the right of the peak the function becomes exponential. In this representation, the function and its derivative are continuous. After making a reasonable guess at parameters for a histogram, fitting was done with `TMinuit`. Time at half-maximum was chosen as t_0.

In the process of tuning code, I tried fitting a smaller Gaussian with the same width and tail 18.8 ns later (period of the RF structure). This did not give an improvement to the fits, and hence was not used to determine the offsets.

2 Wire Plane Alignment

Initially survey numbers were not correctly translated into position of detector components:

1. PWC5 y was off by about 1 cm;
2. PWC6 y was off by about 2 cm;
3. DC1 and DC3 z was off by about 3 cm;
4. DC2 z was off by about 7 cm.

This section describes how wire planes (in x and y) were aligned. Section 3 describes how incorrect z positions were found and corrected.

2.1 Minimization algorithm

The first attempts at alignment were done through minimization of the sum of residuals squared. There are two problems with this method

1. It is slow;
2. Wires which are way off get very high weight.

While the second problem can be mitigated by establishing a more adaptive weight scheme, the speed of the multi-dimensional minimization cannot be improved much. When the total number of parameters is 34 (4 planes in 9 chambers with 2 planes missing).

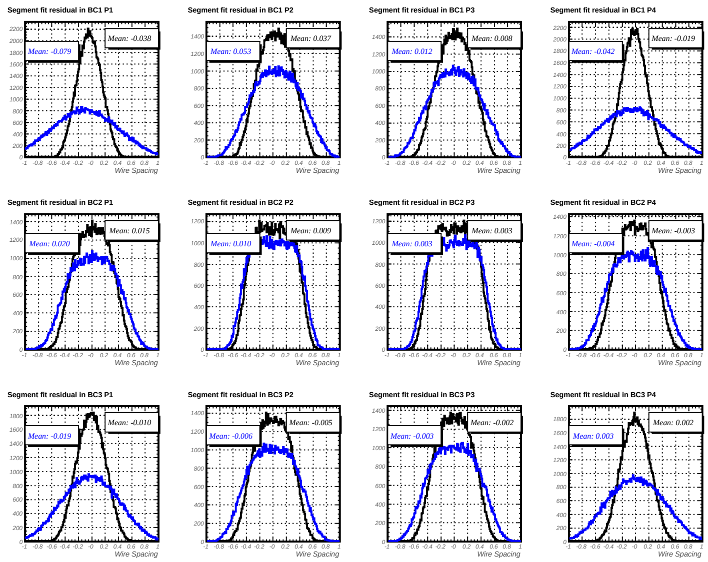

Figure 3: Results from toy Monte Carlo of perfect, unscattered tracks in BC1-3. Intentional misalignment of 0.1 wire spacing is introduced into plane 1 of BC1. Narrower black distribution of residuals is with all 12 wires in the fit and blue wider distributions come from unbiased residuals. One immediately sees that while unbiased distributions are wider, they are much more sensitive to misalignment with the misaligned plane mean residual larger than the next largest mean by 30%. In the case of residuals with all chamber planes in the fit, the BC1 plane 1 mean is only 3% higher than the next largest mean of BC1 plane 2 and distributions give the impression of much better aligned chambers than what is really happening

Alternative approach is to compute the average unbiased residual (that is residual when the wire is not used in the fit) for each chamber plane and shift each plane by 0.3 of the residual. This procedure is repeated until the mean of residuals in every chamber plane is sufficiently close to 0. After each iteration, I remove tracks with at least one residual greater than the sum of 1.5 wire spacing and absolute value of mean residual for the wire plane. In most cases, alignment converges to mean of residuals below 1% of wire spacing in about 10 iterations.

Toy Monte Carlo (`segSim` test binary in `TrkRBase`) shows that unbiased residual points out misalignment much better than residual with the wire in the fit (see Figures 3 and 4). Removing the entire chamber from the fit

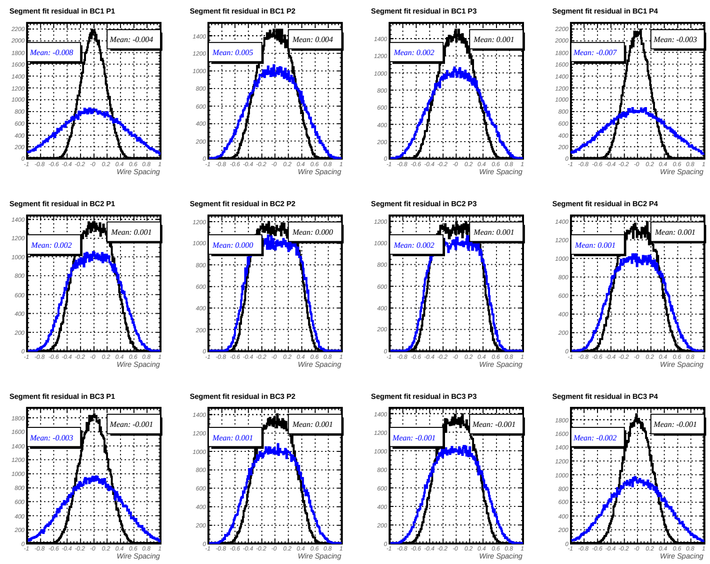

Figure 4: Results from toy Monte Carlo with BC1 plane 1 misaligned by 1% of wire spacing. As in Figure 3, unbiased residuals are more sensitive to misalignment, but with $\sim$ 5000-10000 tracks per run we would not be sensitive to effect of that magnitude. The plots above are made with 10^6 tracks.

reduces the precision of track prediction, significantly broadening residual distributions and gives worse results than the fits with one wire removed. This is especially true in beam chambers where the 12 wire planes do not give sufficient redundancy.

2.2 Alignment Procedure

Alignment of chambers was split into two parts

1. Align BC's to one another;
2. Align all 9 chambers together with 6-chamber secondary tracks and 9-chamber uninteracted beam tracks.

The reason for splitting the two sets of chambers is that most data comes from interaction trigger and therefore the beam track is not present in DC1-PWC6. Thus, we boost statistics for both sets of chambers (nearly every

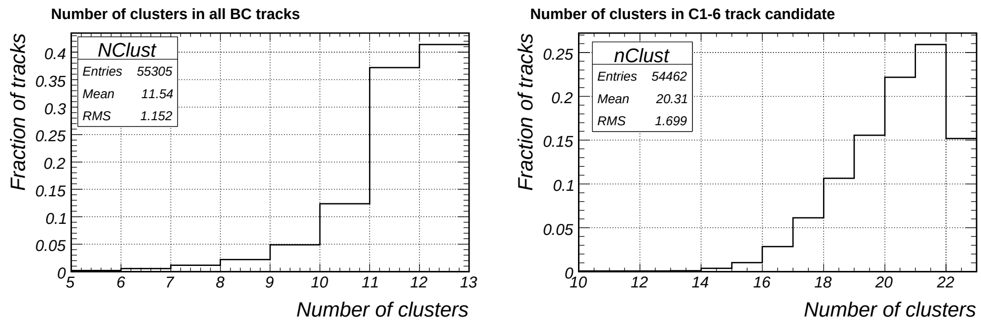

Figure 5: Number of clusters in beam chamber segments and secondary tracks for run 15860 (120 GeV 2% Carbon). While requiring all 12 clusters in a beam chamber track is acceptable, requiring all 22 clusters in a secondary track would come at a heavy toll in statistics.

event gives a beam track and most events give at least one secondary that reaches PWC6), and sample a large area in each chamber with secondary tracks.

Chamber alignment was run as a separate pass on the farm.[2] Besides the `TrkRBase` sequence, alignment job includes `AlignBC` and `AlignChamW0` modules.

`AlignBC` Module I loop through all BC tracks in an event and choose the ones where 12 single-wire clusters are present. The only other event quality cut that is made is to limit attention to events where no more than 3 BC tracks are found. No cut on track quality beyond `TrkSegBuilder` cut of $\chi^2/N_{dof} \leq 1$ is made.

All suitable tracks are saved until the end of the run. The only relevant information is wire number and possibly wire hit time. Wire position in the plane (u) will be varied through alignment iterations.

`AlignChamW0` Module In many respects the module is similar to `AlignBC`. There are three differences:

1. Chamber efficiency is somewhat lower, so requiring all 22 planes to be present in the track would reduce the number of tracks substantially;

[2]Between running alignment pass in September, 2006 and repeating alignment in December 2006-January 2007, modules were moved from `TrkRBase` package into a separate `Alignment` package. I will use the new module names here.

2. The sample contains tracks with 9 chambers and 6 chambers;

3. Fitting relies on the knowledge of magnetic field, which to a degree is an uncertainty.

DC1-PWC6 alignment was done in the same job as BC alignment, but it was executed after BC alignment was finished, so BC alignment constants for the run were picked up. Alignment was done in two stages:

1. Hold BC's fixed, allow variation of wire-0 of large chambers only;

2. Allow variation in all 9 chambers.

Typically, the difference in DC and PWC alignment in the two steps is minimal, but the second step is important to cross check our understanding of alignment by looking at variation of BC alignment. In other words, the output of the first step is taken to compute alignment constants, while the output of the second step is a cross check.

2.3 Reference Coordinate System

Choosing a reference coordinate system is somewhat tricky. Given the approach above, beam chambers plus the two analysis magnets define a reference system for the other 6 chambers.

There is no obvious choice for which chamber planes should be kept fixed during beam chamber alignment, because a priori there is no way to know which plane is most misaligned. After various attempts to hold some planes fixed, I came to conclusion that it is easiest to assume that initial alignment (from survey) is a good starting point. After that, the algorithm gives the largest correction to chamber plane with the largest misalignment, so on average different runs converge to nearly identical set of alignment constants. After the first pass at alignment, I took the average of all alignment runs as the starting point for second chamber alignment pass.

Typical alignment shifts in beam chambers are less than 0.4 mm from the survey, which for a 37 m lever arm of beam chambers could result in a systematic angle shift of 10 μrad. From the perspective of 120 GeV/c beam, this is a 0.4% effect on the kick angle of about 2.5 mrad, so to first order it doesn't matter.

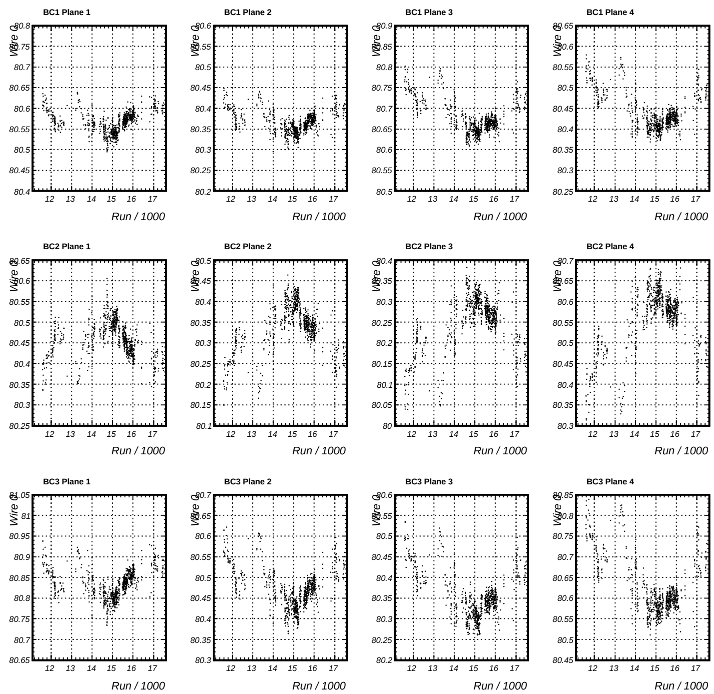

Figure 6: Wire plane alignment results for all 12 BC planes.

2.4 Alignment results - September 2006

Figure 6 shows variation of BC alignment versus run. There are no correlations with beam momentum or sign, and differences of 100 μm over the course of running period seem to be consistent with seasonal and diurnal drifts.

3 Z Alignment

Misalignment in z, even as large as 3-4 cm is not as easy to find and interpret correctly, since typical track angles with respect to z-axis are small and one has to remove correlation of residuals with track angle rather make sure that distribution of residuals is centered at 0. Rotation in xy-plane of a mrad or less is also not easy to determine, especially in DC's where the height of the chamber is about 1.2 m, so a 1 mrad rotation would produce a systematic

	Plane 1	Plane 2	Plane 3	Plane 4	Net shift X (cm)	Net shift Y (cm)
BC1	80.57	80.36	80.67	80.43	+0.001	−0.002
BC2	80.46	80.34	80.26	80.56	−0.010	+0.009
BC3	80.83	80.47	80.35	80.62	+0.007	−0.032
DC1	256.83	257.43	256.34	256.80	+0.127	−0.180
DC2	224.31	257.68	256.78	225.11	+0.157	−0.430
DC3	224.69	256.36	257.47	225.04	+0.129	+0.025
DC4	224.94	256.67	256.41	225.11	+0.090	−0.104
PWC5	319.00	316.58	N/A	N/A	−0.446	+1.177
PWC6	319.98	313.80	317.02	323.16	−0.140	+1.994

Table 1: Summary of wire plane alignment results from September, 2006. Numbers for BC's are averages over all runs, while for DC1-PWC6 the offset is calculated from distribution of residuals versus q/p (like Figure 8), taken at $q/p = 0$.

0.2 wire spacing offset of residual mean at the top and bottom of the chamber.

In case of beam chambers, track angles and chamber area are so small that we have no hope of checking z-alignment or rotations. At the same time, experiment is not as sensitive to such misalignment.

3.1 Signs of trouble

One of the first signs that something is wrong was the fact that track momentum changes systematically when DC1 is taken out of the fit (see Figure 7).

More troubling signs came from the fact that wire alignment was correlating with momentum (see Figure 8).

A kind of breakthrough was to look at dependence of residuals on dx/dz, where correlation is much stronger (see Figure 9). This meant that the effect must be observable in field-off data, and most certainly it was.

3.2 Software (technical details)

Two similar modules were created for field-off and field-on z-alignment. The reason is that field-on (`AlignChamZ`) module uses `TrkCand`'s while field-off (`AlignChamZNoBF`) module picks up 5+ chamber straight lines, which are more plentiful than `TrkCand`'s in field-off data. Given the fact that this

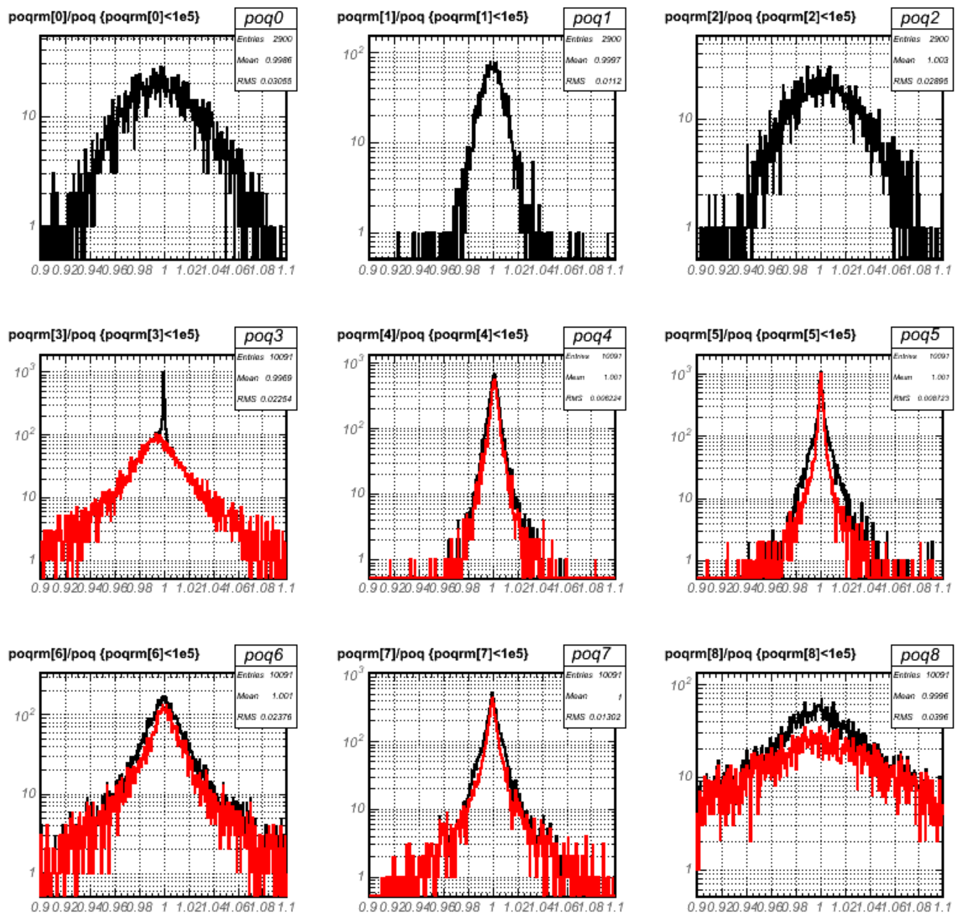

Figure 7: The 9 plots generated in May, 2006 show distribution of the ratio of track momentum when a chamber is taken out of the fit and track momentum with all 6 or 9 chambers. Black histograms include all tracks, red histograms are tracks without BC information. Top row is BC's, middle row – DC1,2,3 bottom row – DC4 and PWC's. Notice that when DC1 is taken out of the fit and no BC information is available, on average momentum gets smaller by 1%.

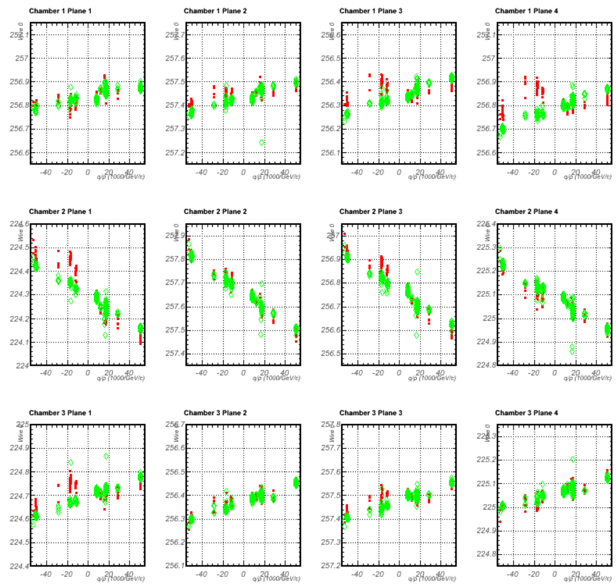

Figure 8: This set of plots shows clear correlation of wire alignment offsets with momentum. Small red dots come from alignment with 9 chambers, and green diamonds from alignment with 6 chambers. Results come from more than 2000 runs.

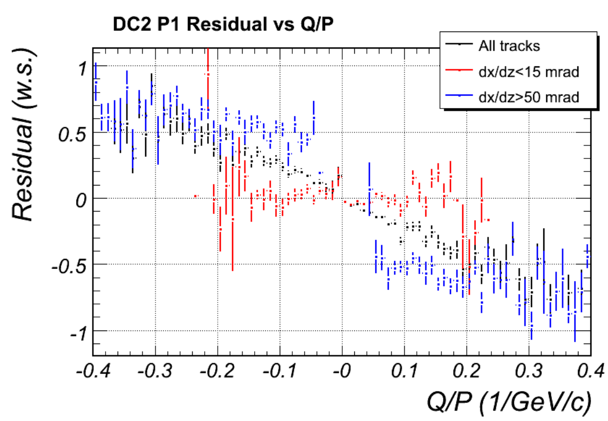

Figure 9: Shown are residuals vs q/p with different cuts on track angles. When tracks with $dx/dz < 15$ mrad are selected, there is no correlation of residuals with q/p. This suggests that correlation with dx/dz is much stronger than with q/p.

is a much more sensitive process than wire plane alignment, z-alignment job description is not included into `BatchProc` package, but in `Alignment` package you can find `alignZNoBFjob.xml` and `trkAlignZjob.xml`.

Although `trkchamgeo` table is equipped to store wire angles and chamber z, it is more practical to extract shifts from job log file (or standard out if the job is run on the command line). To streamline the process on the farm, `reformatAlignZ.sh` script was created to extract numbers from log files and save them to text file. Then ROOT macro `resToTree.C` can convert text file to ROOT tree, which is used to make the plots like in Figures 10, 12, and 13

With a total of 12 parameters (z and xy-rotation), this task is adequate for `TMinuit` fitter, especially since reasonable results can only be obtained when at least 3 parameters (2 z's and an angle) are held fixed. The module accumulates track wires for the entire run, and at the end of the job, it gets `TMinuit` to minimize the sum of track χ^2.[3]

3.3 Approach to alignment

Alignment in z is a bit tricky for the following reasons:

- It requires two reference points so that the overall scale is set;
- Misalignment produces subtle effects which take time and careful consideration to be interpreted correctly;
- Most data we have has JGG and Rosie fields on, introducing further complications.

Initial attempts at z alignment were not satisfying the first requirement. The effect was that minimization algorithm was stretching the experiment producing unreasonable shifts in z. The first way out was to fix DC1 and limit displacement of chambers 2-6 to ± 10 cm. We noticed that minimization algorithm shifted DC2 upstream (towards negative z), while the other chambers were "stretched" downstream (towards positive z).

The final solution was to fix DC1 and PWC6 which are separated by 20 m. This way a 5 cm z misalignment (taken as a worst scenario) of either chamber would be changing z scale by 0.25%. Result of this minimization

[3]It is also possible to achieve nearly identical results by minimizing the correlation of residual and track dx/dz, however errors on parameters do not make sense and minimization takes longer since after track fit each residual must be computed.

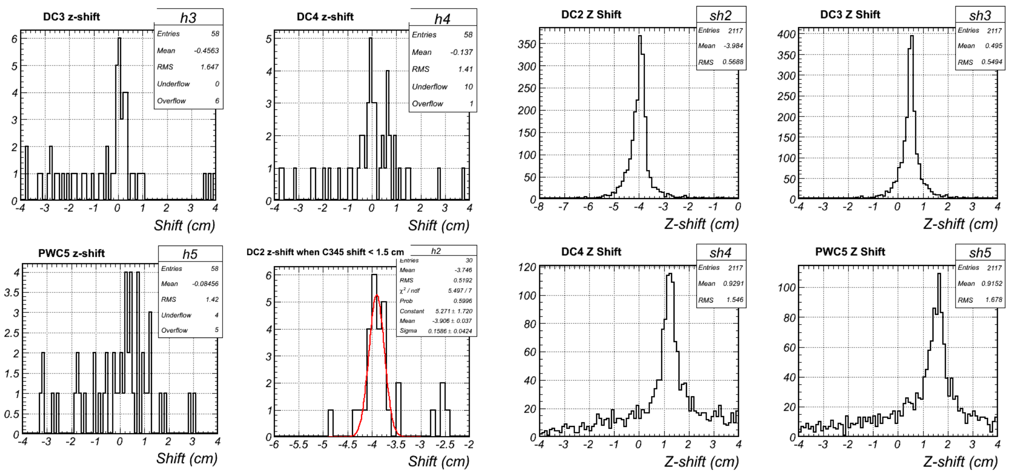

Figure 10: Results from field-off (left) and field-on z-alignment fits with DC1 and PWC6 z fixed. Notice that while field-off data does not want significant shifts to DC3, DC4, and PWC5 z positions, field-on data wants to have the three chambers shifted downstream. Since field-on data has the extra unknown (field map locations and relative strength), we have no choice but to trust field-off data even though there is very little of it.

using all of the field-off and field-on data was that DC2 had to be shifted upstream by about 4 cm. Holger Meyer was able to confirm with a tape measure that DC2 was indeed incorrectly positioned with respect to DC1 and DC3 by about 4.5 cm.

4 Fine Tuning

With a lot of work put into recalculating geometric constants from survey measurement, a number of important corrections were made:

1. DC1-3 shifted upstream by 3 cm (making the total shift of DC2 of 7 cm);
2. PWC5 shifted up in y by 1 cm;
3. PWC6 shifted up by 2 cm in y;
4. Rosie field center shifted by 5 cm upstream in z.

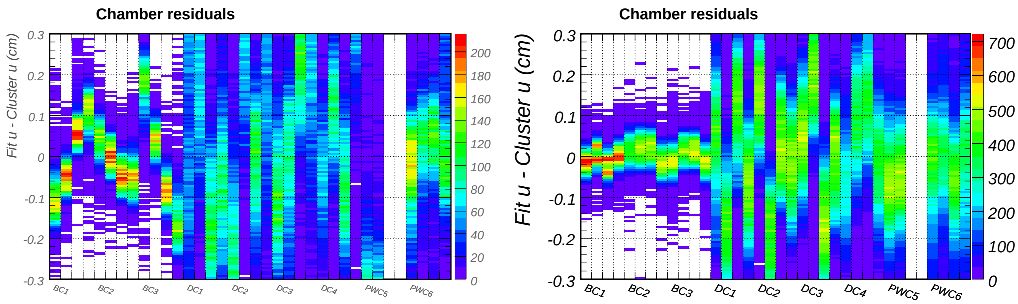

Figure 11: Shown are residuals prior to wire plane alignment with geometry constants from September, 2006 (left) and with geometry constants from December, 2006 (right). The fact that all residual means are smaller than wire spacing gives confidence that survey information is correct and was correctly converted into ROOT geometry.

Two other important changes is expanded JGG field at the upstream of the map, which adds 0.25% of $\int Bdl$, and the scaling of field maps which is done using the ratio of Hall probe readings during the run to reading during Ziptracking. The previous scaling was based on a guess of locations of Hall probes, and was therefore not as precise.

Geometric shifts of the chambers have a profound effect on residuals before any chamber alignment is done (see Figure 11). With this geometry, the average wire offsets for all chambers using field-off data are given in table 2.

4.1 Z-locations and XY-rotations

To judge how well new geometry constants agree with data, z-alignment and xy-rotation cross check was repeated. This time in three steps.

4.1.1 One chamber at a time

With 5 chambers held fixed, z and xy-rotation were varied for one chamber. The exercise was repeated 6 times, results are shown in Figure 12.

Evidently, the fact that DC1-PWC5 distance is 7.2 m and PWC5-PWC6 distance is 12.83 m makes it very difficult to say anything about PWC6, so we have to rely upon survey data and wire plane alignment for PWC6.

	Plane 1	Plane 2	Plane 3	Plane 4
BC1	80.74	80.50	80.73	80.44
BC2	80.41	80.27	80.23	80.55
BC3	80.78	80.46	80.45	80.74
DC1	256.82	257.42	256.34	256.81
DC2	224.02	257.44	256.51	224.92
DC3	224.34	256.09	257.13	224.85
DC4	224.68	256.32	256.09	224.72
PWC5	320.86	320.48	320.5	320.5
PWC6	321.19	320.41	321.20	321.13

Table 2: Wire offsets using December 2006 geometry. Notice that all offsets are very close to $(N_{wire} + 1)/2$.

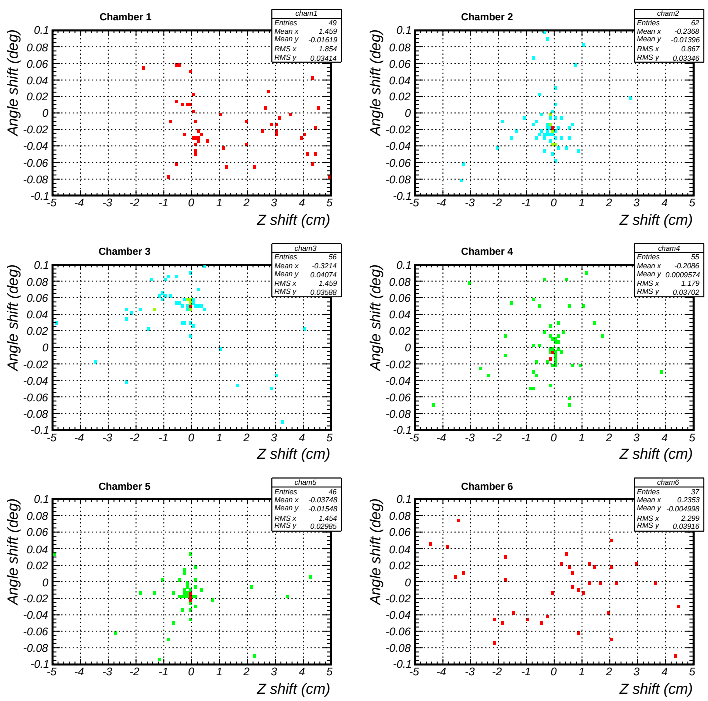

Figure 12: These plots are made from field-off alignment, allowing z and xy-rotation of exactly one chamber to vary. While z locations do not change significantly, DC3 comes out with the largest rotation of $0.05°$.

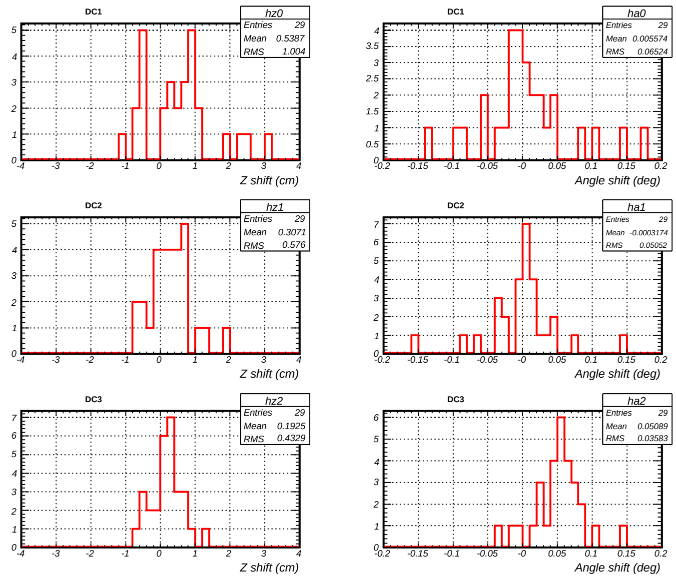

Figure 13: These plots were made with DC1-3 z and rotation free to vary. Histograms for each chamber are plotted with the same cut on fitted shifts for every chamber: $|z_{shift}| < 4$ cm and $|\theta_{shift}| < 0.2°$. Out of 115 field-off runs, only 29 survive this cut!

DC1-PWC5 z-positions are consistent within a few mm, but it is clear that at least one of the chambers is rotated with respect to the others. Given the fact that DC3 is the only one that has the largest fitted rotation and its sign is **different** from all other chamber fitted rotations, suspicion is that DC3 rotation matrix is off by about 1 mrad.

4.1.2 Letting DC1-3 loose

With December 2006 geometry having shifted all 3 chambers (DC1-3) by 3 cm, it is instructive to see how sensitive field-off data is to location of the triplet. Z-alignment code was rerun with z and xy-rotation of DC1-3 free.

Plots on Figure 13 summarize results from 115 field-off runs. Only one quarter of the runs produce reasonable z and angle shifts! This is unfortunate, since better precision on determination of correct rotation and z is not possible. One can make the following observations:

1. Rotation of DC1 and DC2 is consistent with rotation of DC4, PWC5

and PWC6;

2. DC3 needs to be rotated by $0.055 \pm 0.004°$;

3. There may be still be a small misalignment in z, with DC1 wanting to go downstream by 0.5 cm, DC2 by 0.3 cm, and DC3 by 0.2 cm.

4.2 Rotating DC3

Final check is done by rotating DC3 by $-0.055°$ around z-axis, and re-running field-off alignment with DC1-3 z and DC3 angle free. Figure 14 shows that the chamber is rotated correctly, but the z-shifts are comparable to those in Figure 13. Given the size of the desired shifts and the fact that they may come from the fact that residual and Earth magnetic fields are not taken into account, it is not necessary to shift chambers unless we obtain more evidence to the contrary.

The 30 runs which make up Figure 14 come from 5 different time periods:

Mar 21-22, 2005:	13425 13426 13427 13428 13429 13430 13431 13432 13433 13434 13437
Jun 15, 2005:	14520
Jul 14, 2005:	14966 14967 14968 14969 14971 14972 14973 14974
Jan 10-12, 2006:	17269 17270 17273 17274 17275 17276 17277
Feb 17-18, 2006:	17555 17556 17564

With these data, we conclude that the discrepancy between survey data and tracking is not run-dependent, and can be adequately corrected with one rotation for the entire running period from January 2005 to February 2006.

4.3 Rotating magnetic field map components

With z-positions and xy-rotations of chambers under control, results of field-on alignment were still a disappointment (see Figure 15). However, compared to Figure 8 this does look better, except for the vertical-measuring second plane of both PWC's.

Of course, component of magnetic field that affects the kick in y most strongly is B_x. B_z does not play a significant role because track angles to z-axis are small. Figure 16 shows that in the center of the magnet ratios B_x/B_y and B_z/B_y are different from 0 to the precision of the measurement.

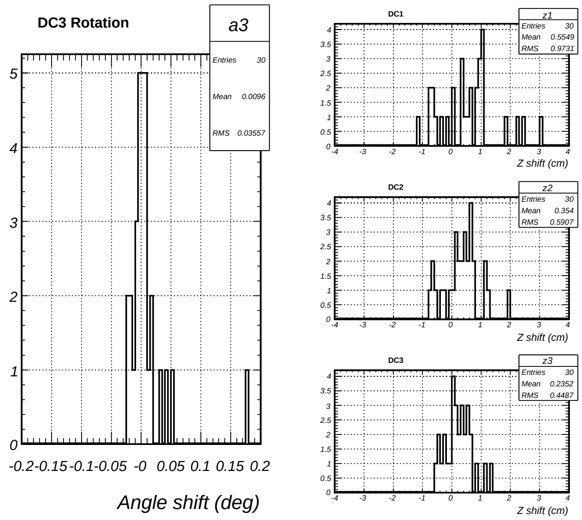

Figure 14: Results of field-off alignment with DC3 rotated by $-0.055°$. The plots are done with the same cut as those in Figure 13.

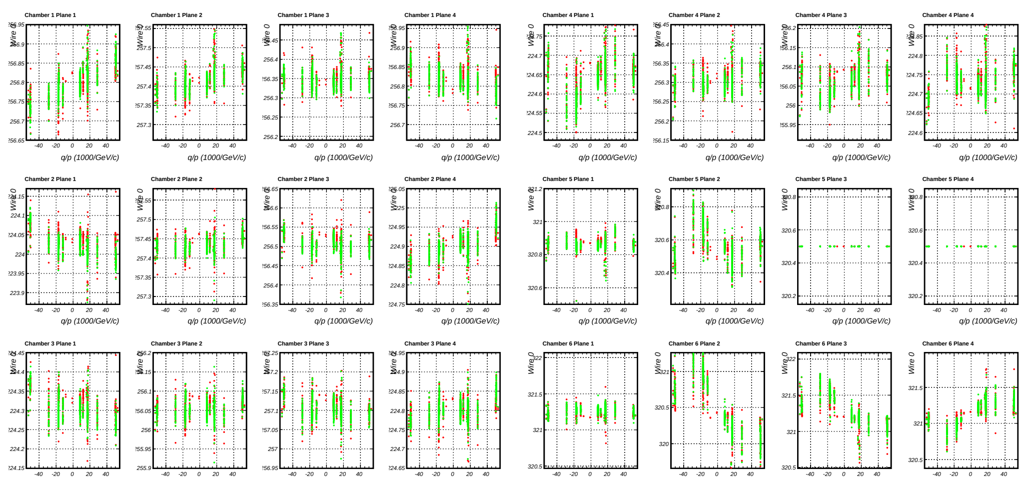

Figure 15: Results of alignment with corrected chamber z and xy-rotations. While alignment of DC's looks OK, PWC5-6 plane 2 have rather large correlation with beam q/p. Note that histograms have different y-ranges.

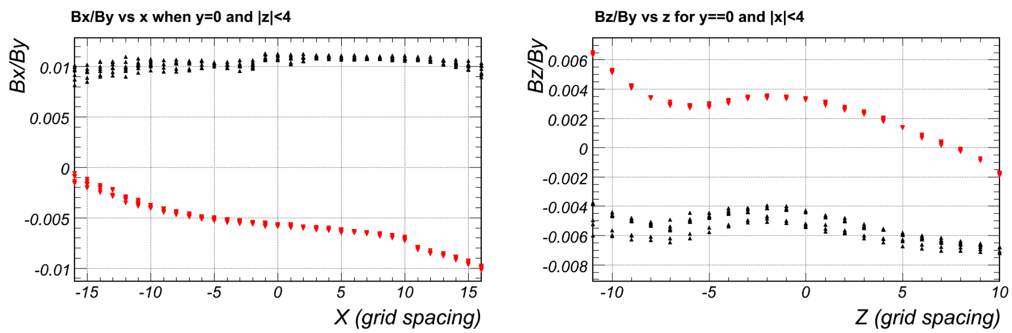

Figure 16: The ratio of B_x/B_y and B_z/B_y for the two magnets. JGG is in black up-pointing triangles; Rosie is in red down-pointing triangles. All distances on these plots are measured in 2 inch grid spacing.

Moreover, the ratio is of the same order of magnitude but opposite in the two magnets.

When magnet measurements were done, position of the grid points was determined with precision of 100 μm or better, but rotation of the Hall probes was not possible to get very accurately for lack of lever arm. The difference between JGG and Rosie Ziptracking is that the Hall probe was rotated by $180°$ about the y-axis. Thus, if the probe was rotated during the scan, the effect of B_y bleeding into B_x and B_z should be approximately equal and opposite for the two magnets.

In order to verify that the correlations shown in Figure 15 are caused by B_y bleed into B_x, module `AlignRotB` was written. It accumulates beam tracks with at least 30 single-wire chamber hits and minimizes the sum of χ^2 by rotating components of magnetic field about z-axis through

$$\begin{cases} B'_x = B_x \cos\theta + B_y \sin\theta, \\ B'_y = -B_x \sin\theta + B_y \cos\theta. \end{cases} \tag{2}$$

The module was run on 1865 runs. NuMI and K-mass runs were excluded, as well as runs with less than 5000 triggers. Out of 1336 runs that found more than 200 tracks, 696 runs did not hit the limit of ± 20 mrad for either rotation and had errors less than 5 mrad associated with the measured rotation.

Results are shown in Figure 17. The strong correlation of rotation angles with beam momentum comes from small misalignment of the wire planes, as one set of alignment constants was used for all runs. However, misalignment has a small effect on lower momentum data, where the observed kick is large,

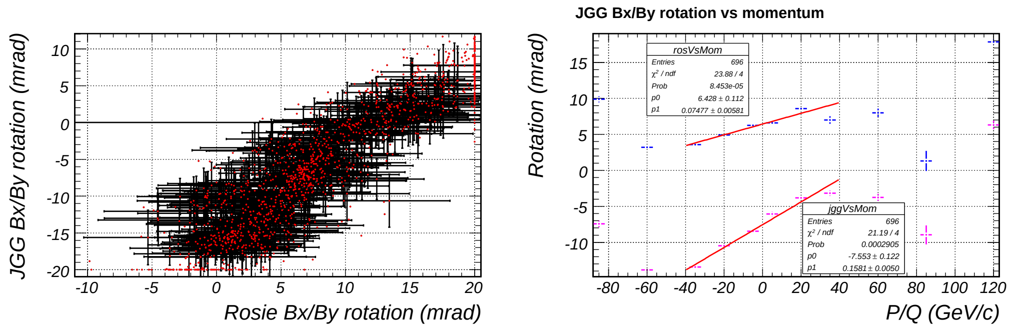

Figure 17: Shown are results of rotation of beam components about the z-axis. The strong correlation of rotation with beam momentum is not surprising. The total predicted kick at PWC6 for 120 GeV particle is 0.8 mm (less than $\frac{1}{3}$ wire spacing) using the original field map. Therefore, a small misalignment will be compensated by magnetic field components. Note however, that $(0,0)$ point (no rotation) is excluded by these fits!

so taking y-intercept of linear fit to points for beam $|p/q| < 40$ GeV/c is the right thing to do. Results are unambiguous that JGG wants rotation of -7.5 ± 0.1 mrad and Rosie wants rotation of $+6.4\pm0.1$ mrad. Working under assumption that the rotation needs to be equal and opposite, we rotate each field map by 7 mrad so as to make B_x-B_y correlation smaller in the middle of the magnet.

We do not have a clean fast way of determining the amount B_y bleed into B_z from data, so relying on Figure 16, the field maps are rotated by 3 mrad.

5 Generating Alignment Offsets

5.1 Run Selection

Chamber alignment jobs were rerun after all fine-tuning adjustments were made. Out of 1945 runs, 1236 had enough statistics to do 9-chamber alignment. I focus on those runs as the most reliable. However, as stated above, alignment constants from `AlignBC` are taken for BC's and constants with BC's fixed are taken for large chambers. The only other alignment quality that I require are fairly loose cuts on deviation from the mean on every chamber plane. The following cuts were used:

- BC's: 0.2 wire spacing

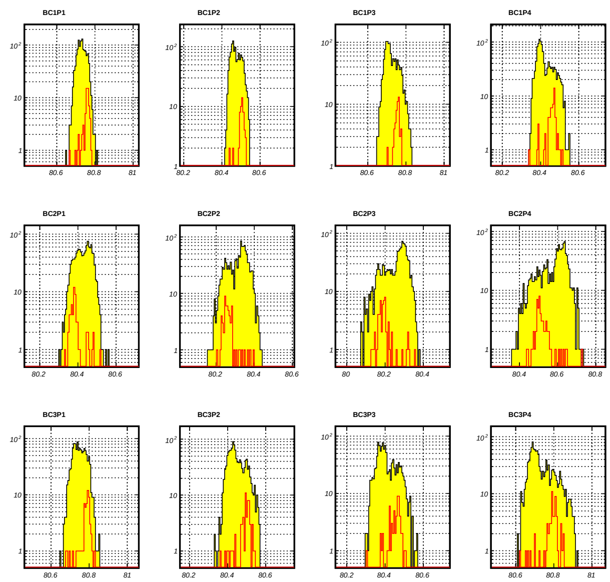

Figure 18: Alignment summary of BC's. See explanation in text.

- DC's: 0.1 wire spacing
- PWC5: 0.15 wire spacing
- PWC6: 0.24 wire spacing

The reason for the cuts is to remove potential bias due to runs where alignment clearly failed. All BC data passed the cuts, and in chambers 1-6, the following is distribution of number of runs rejected by each chamber (a total of 59 runs):

DC1	DC2	DC3	DC4	PWC5	PWC6
16	14	20	31	28	38

Figures 18, 19, 20 show alignment constants of the 1177 runs that passed the cuts (wire offset shown in solid yellow) and 59 rejected runs (red line).

5.2 Selection of Constants

Figure 21 shows distribution of alignment constants as a function of run. It is clear that variations in alignment constants of beam chambers are measurable

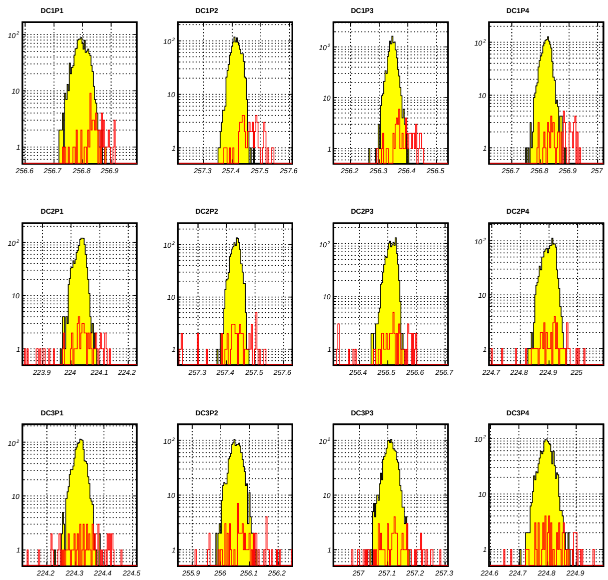

Figure 19: Alignment summary of DC123. See explanation in text.

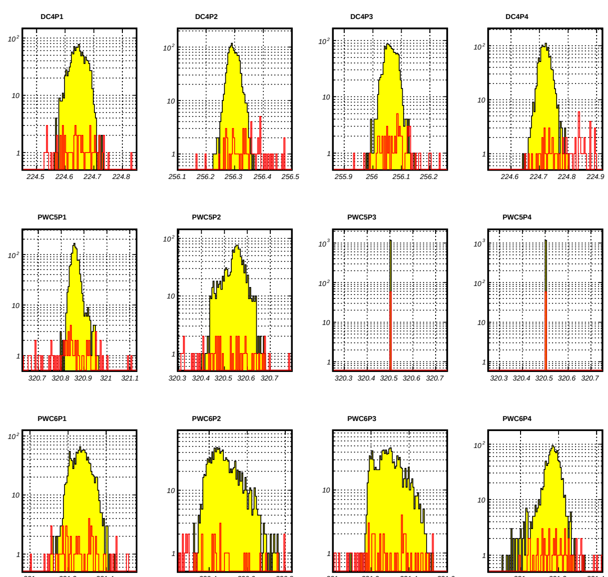

Figure 20: Alignment summary of DC4 and PWC's. See explanation in text.

	LH2	NuMI	Thin	Empty LH2	Empty Thin	K-mass
# of runs	443	246	842	92	245	79
# rejected	212	190	210	34	55	67
% rejected	47	77	25	37	22	84

Table 3: Summary of all rejected runs by target type. This table includes runs removed because of lack of 9-chamber alignment and 59 runs that did not pass the cuts on wire-0.

(this conclusion does not change from results shown in Figure 6), so the drifts ought to be taken into account. In the case of the large chambers, variation is significantly smaller, and as Figure 22 shows, correlations with beam q/p are comparable to the total spread of wire offsets. With alignment constants determined this well, it is unreasonable to vary the constants from run to run. The danger of introducing a bias is larger than calculating systematic error due to the potential small misalignment.

The averages of alignment constants for each chamber are shown in Table 4. The values listed for largest chambers will be used for alignment of all runs. Table 5 shows the RMS and total width of every wire-0 distribution. These numbers tell us that by using one set of numbers for all chambers we would not be introducing a misalignment larger than 9% of wire spacing into any chamber plane in any run, with exception of PWC6 and vertical-measuring plane in PWC5. These numbers can be folded into weights associated with each chamber cluster so that errors on track parameters are correctly computed.

6 Conclusion

Chamber alignment was a time consuming affair lasting 1.5 years from July, 2005 to January 2007. In the process a number of geometry errors were corrected and rotation of Ziptrack Hall probe mount compensated in the magnet field map.

While further improvement to understanding of alignment is possible, from the point of benefit to track position and momentum measurement, we are at the point of diminishing return as of January, 2007. With the largest alignment uncertainty RMS of 7.7% of wire spacing in PWC6, improvement

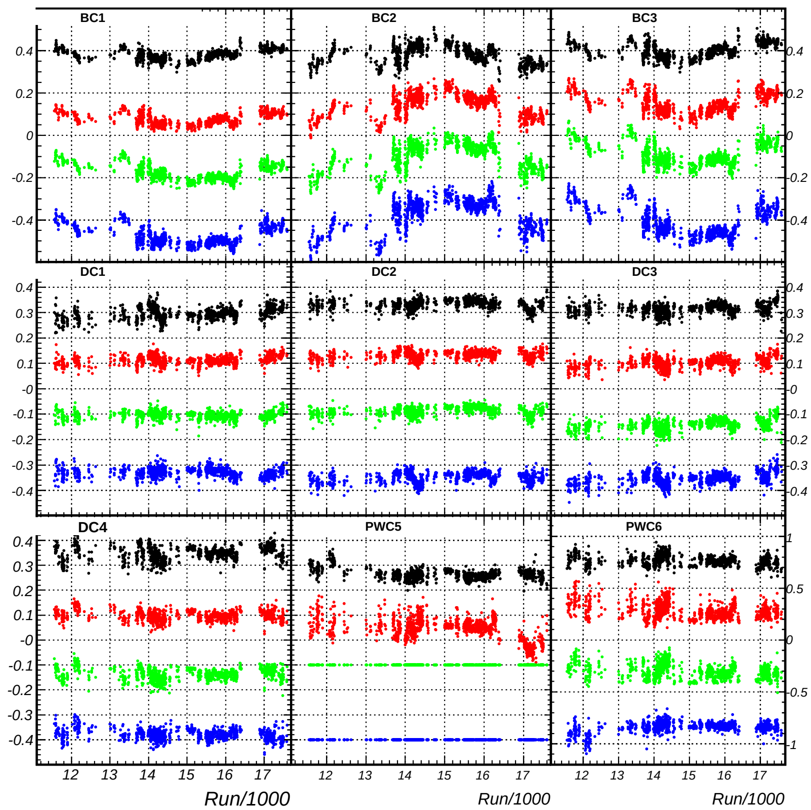

Figure 21: Alignment results for best runs using the fine-tuned rotations and field map. In each graph from top to bottom are planes 1 to 4. The vertical scale is in wire spacing. Note that the scale for PWC6 is different from other chambers.

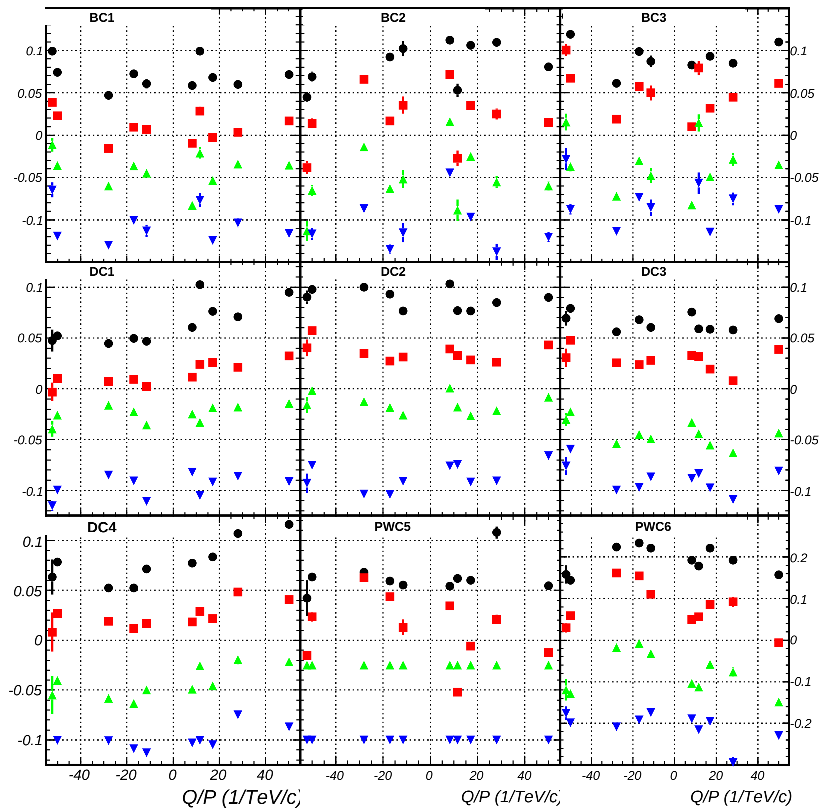

Figure 22: Alignment results versus beam q/p for best runs. The correlations are much smaller than prior to rotation of magnetic field components (Figure 15, but they do exist.

	Plane 1	Plane 2	Plane 3	Plane 4
BC1	80.731	80.476	80.725	80.423
BC2	80.429	80.314	80.254	80.577
BC3	80.750	80.449	80.410	80.737
DC1	256.796	257.413	256.346	256.820
DC2	224.031	257.432	256.512	224.900
DC3	224.314	256.052	257.108	224.796
DC4	224.646	256.296	256.062	224.720
PWC5	320.862	320.544	320.500	320.500
PWC6	321.268	320.482	321.299	321.164

Table 4: Average alignment constants for all 9 chambers in wire spacing. BC averages are listed for completeness.

	Plane 1		Plane 2		Plane 3		Plane 4		Avg	Avg (μm)
BC1	2.4	16.3	2.7	12.7	3.5	18.2	4.2	20.8	3.2	32
BC2	4.2	25.5	5.2	27.9	6.3	30.8	7.2	37.3	5.7	58
BC3	3.4	20.7	4.4	23.9	5.2	27.1	6.4	31.0	4.8	49
DC1	2.4	15.8	1.8	12.5	1.5	13.8	1.7	13.6	1.8	64
DC2	1.8	12.5	1.6	10.6	1.7	11.3	2.0	13.0	1.8	56
DC3	1.9	15.8	2.0	14.0	2.1	15.0	2.3	18.7	2.1	66
DC4	2.8	16.8	1.9	14.1	2.2	16.7	2.0	15.9	2.2	70
PWC5	2.0	16.9	4.5	27.5	-	-	-	-	3.3	98
PWC6	4.9	33.9	7.7	44.6	7.2	43.3	4.7	43.0	6.1	184

Table 5: RMS of wire plane alignment constants and the total width (difference between largest and smallest wire-0) of every plane in percent of wire spacing. The last two columns show average of the RMS values in percent of wire spacing and in microns. BC's are shown for comparison. Note that the total range is always a few percent of wire spacing smaller than the cuts used to select the 1177 good runs.

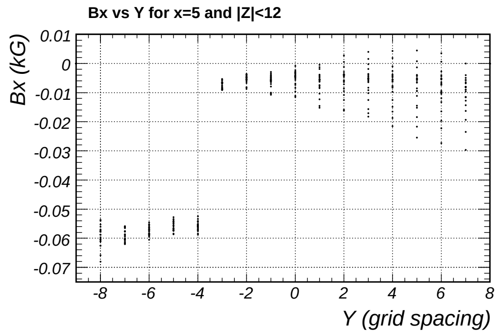

Figure 23: One example of clearly discontinuos B_x in Rosie magnet. While the field is small, it will have an effect on tracks that traverse that space in the magnet.

to current offsets would most likely have to come from vertexed events where redundancy of measurements is much larger than in single track fits. At that level of understanding of alignment, a number of effects not taken into account so far become important:

- xy-rotations of 0.2 mrad introduce a 7% wire spacing effect.
- Earth's magnetic field in the experimental hall can contribute up to 0.5% to $\int Bdl$ over the 60 m of experiment.
- Survey chamber xz- and yz-rotations introduce an offset of up to 1 cm in wire z location. Current tracking does not take that into account, yet there is indication of ~ 5 mm misalignment in z.
- Visible discontinuities in field maps (example in Figure 23).

All these effects have minimal systematic effect on tracking, but they have to be taken into account especially if tracking is to rely upon using drift times in DC1-4. As a measure of requirement upon alignment one can remember that a 120 GeV/c track gets deflected from a straight line by about 1.8 cm (6 wire spacings) at DC4, so a 0.5 wire spacing misalignment can have a 10% effect on momentum measurement. Based on our results, we should be reconstructing 120 GeV/c momentum with a $< 2\%$ systematic uncertainty. Of course, momentum systematic uncertainty due to alignment is smaller for particles of lower momentum.